Cruise Report

SONNE cruise SO 128

ARABWOCE

Male - Muskat

8. - 29. January 1998

Institut für Meereskunde
an der Universität Kiel
Düsternbrooker Weg 20
24105 Kiel - Germany

Untersuchung der Monsunzirkulation im Arabischen Meer

Investigation of the monsoon circulation of the Arabian Sea

Fahrtbericht
Cruise Report

SO 128

ARABWOCE

(BMBF Projekt 03G0128A)

Fahrtleiter/chief scientist:

Prof. Dr. Friedrich Schott
Institut für Meereskunde
an der Universität Kiel
Düsternbrooker Weg 20
24105 Kiel

Tel: 0431-597-3820
Fax: 0431-597-3821
e-mail:fschott@ifm.uni-kiel.de

Zusammenfassung

Die Forschungsfahrt SO 128 des FS „SONNE“ vom 8. bis 29. Januar 1998 von Male nach Muskat wurde vom Institut für Meereskunde an der Universität Kiel im Rahmen des internationalen World Ocean Circulation Experiments (WOCE) durchgeführt. Gesamtziel von WOCE ist es, eine verbesserte Zustandsbeschreibung des Ozeans zu erlangen, Modelle für eine verbesserte Beschreibung der ozeanischen Zirkulation und letztlich für die Vorhersage von Klimaveränderungen zu entwickeln und die dafür nötigen Daten im Weltozean zu sammeln. Die Fahrt war ein Beitrag zum nationalen deutschen WOCE Programm, das vom Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie gefördert wird.

Die Hauptuntersuchungsaufgabe während der Reise SO 128 war es, den Austausch von Wassermassen über den Südausgang des Arabischen Meeres entlang eines Zonalschnittes bei 8°N zu messen. Ein weiterer Schwerpunkt war die Untersuchung der Somalistrom-Zirkulation während des Nordostmonsuns. Daten aus dieser Jahreszeit fehlen bisher fast vollständig und das WOCE Indische Ozean Experiment im Jahr 1995 im Arabischen Meer hatte sich ausschließlich auf den Sommermonsunresponse beschränkt. Die Daten dieser Reise aus dem Nordostmonsun zusammen mit den Südwestmonsun Daten von 1995 und dem 8°N Schnitt durch das Arabische Meer im August 1993, aufgenommen mit FS SONNE (SO 89), bilden einen idealen Datensatz, um den Gegensatz zwischen Winter- und Sommermonsunzirkulation bei 8°N und im Arabischen Meer zu untersuchen.

Messungen die durchgeführt wurden, waren hoch auflösende Messungen von Temperatur, Leitfähigkeit und Druck durch CTD-Profile, kontinuierliche Messungen der Strömungen in den oberen 400 m der Wassersäule mit dem im Schiff installierten Akustischen Doppler Strömungsprofiler (ADCP), Geschwindigkeitsprofile über die gesamte Wassersäule von einem an die CTD angebrachten ADCP und dem Pegasus-System, Freon-Verteilungen aus den Wasserschöpfern, XBT-Profile und kontinuierliche Aufnahme von Oberflächentemperaturen und Salzgehalten, meteorologischen Parametern und Tiefenmessungen. Die Fahrtroute und die Lage der Stationen sind in Abbildung 1 dargestellt.

Die Fahrt stand in einem unmittelbaren Zusammenhang mit der SONNE Reise SO 127 (BENGALWOCE, Dr. D. Quadfasel) die ähnliche Zielsetzungen verfolgten.

Summary

RV „SONNE“ cruise SO 128, during 8 to 29 January 1998 from Male to Muscat was carried out by Institut für Meereskunde Kiel within the context of the World Ocean Circulation Experiment (WOCE). The main goal of WOCE is to derive an improved description of the World Ocean and to provide the data for the development of models for a better description of the oceanic circulation that will eventually serve as tools for the prediction of future climate changes. The cruise was a contribution to the German WOCE component and was funded by the Federal Ministry of Education, Science, Research and Technology (BMBF).

The main objective during cruise SO 128 was to measure the exchange of water masses and transports across the exit of the Arabian Sea along a zonal section at 8°N. A particular objective in the northwestern Arabian Sea was the determination of the Somali Current circulation during the northeast monsoon. Data from this season are almost totally lacking, and the WOCE 1995 Indian Ocean Experiment in the Arabian Sea had solely focussed on the summer monsoon response. The northeast monsoon data from this cruise together with the southwest monsoon data from 1995 and the 8°N section in the Arabian Sea measured with RV „SONNE“ in August 1993 (SO 89) will be an ideal data set to investigate the monsoon circulation changes at 8°N and in the Arabian Sea.

Measurements carried out were high resolution measurements of temperature, conductivity and pressure by CTD casts, continuous current profiling in the upper 400 m of the water column using shipboard Acoustic Doppler Current Profiler (ADCP), top to bottom velocity profiles from a lowered ADCP and the Pegasus system, freon distribution from the water samples, XBT-probes and continuous surface temperature and salinity distributions, meteorological parameters and depth soundings. The cruise track and the location of the stations are shown in Figure 1.

The cruise was carried out in close co-operation with SO 127 (BENGALWOCE, Dr. D. Quadfasel) where similar objectives were addressed.

1. Narrative

Cruise SO 128 began on 8 January 1998 out of Male, Maldives. Originally the plan had been to start the 8°N section at the eastern shelf edge, off India, as our 1993 summer monsoon coverage of that section (cruise SO 89) had done. However, on very short notice, Indian approval was declined and a second best route of that section had to be chosen which was from Sri Lanka over the Maldives and then continuing westward along 8°N. The first 21 stations, up to the western 200 nm limit of the Maldives, were measured by the predecessor group (IfM Hamburg, Dr. D. Quadfasel) on cruise SO 127. Our observations began on 9 January with CTD hydrography, oxygen and freon/tracer measurements; and with current profiling by shipboard ADCP as well as by an ADCP, lowered with the CTD/rosette (LADCP). The observations along the 8°N section ended on 17 January at 54°E, at the Somali EEZ limit (stat. 30, Fig. 1).

Along the 8°N section, one objective of interest was the amount of winddriven transport (Ekman transport), analyzed in comparison of directly measured near-surface currents and those determined from geostrophy, which is an important element in the meridional heat exchange. Unexpectedly large circulation cells were found in the ADCP observations along that section. In the east there were indications that we encountered the clockwise-circulation cell named „Laccadive High“ that appears to exist each winter between India and the northern Maldives. Other objectives along that section were the deep currents in the Arabian Basin east of the Carlsberg Ridge and in the Somali Basin west of the Chain Ridge.

From 17 - 21 January „SONNE“ worked her way northward toward Socotra along approx. 53°E (stations 31-46), where we had a moored array deployed between April 1995 and October 1996. Along that section acoustic bottom transponders were still operational at 5 locations since April 1995 and Pegasus current profiles were obtained at all of them for comparison with the lowered ADCP. The currents at the northern end of that section (stations 43-46) were going eastward, apparently recirculating the waters that are going westward further to the south.

During 20 - 21 January, the currents and water masses in the 1100 m deep passage between Socotra side and the Horn of Africa were investigated (stations 47-57) and it was found that the surface circulation moved northward through the passage but that at depth the Red Sea Water (RSW) was entering at the western side. This confirmed our moored station observations showing a near-permanent entry of RSW through that passage and allows us transport estimates for the RSW.

On 22 January, an eastward section was begun along 12.5°N, starting at 54°41'E at the eastern shelf edge off the island of Socotra (stat. 58). That section showed strong northeastward near-surface flow, apparently a continuation of the eastward branch we had found just south of Socotra earlier. We therefore decided to insert a short southward cruise leg of several hours to cross that circulation branch and be able to determine its transport. After that was accomplished (stations 64-66) the eastward section was continued to 56.5°E (stat. 68), from where a northward leg was started leading to the south coast of Oman (stat. 82). Along that section the ADCP observations seemed to indicate that the northeastward flow was first turning northward then recirculating westward. Transports of that structure were fairly large, in the order of 15 Sv.

On 26 January, the 56.5°E section was terminated off Oman and along the way toward the Gulf of Oman an offshore XBT section was carried out until position 19°40'N, 59°45'E, from where a last slant section with 4 CTDs (stations 83-86) was leading back to the shelf to observe the flow structure off the continental shelf during the NE monsoon. The observational program was terminated at this point and „SONNE“ began the last segment toward Muscat where we arrived in the morning of 28 January 1998.

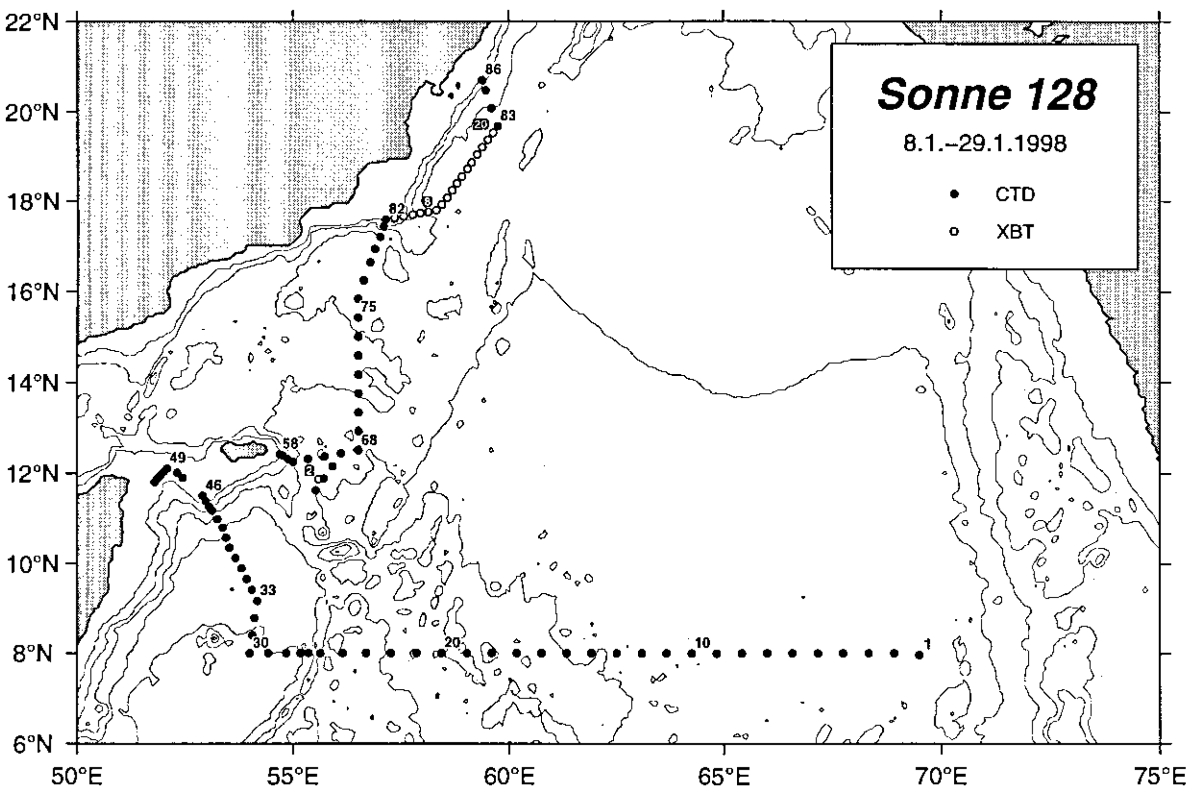

Figure 1: *Location of CTD/LADCP stations (dots) and XBT-profiles (open circles) during cruise SO 128.*

Abbildung 1: *Lage der CTD/LADCP Stationen (Punkte) und XBT-Profile (offene Kreise) während der Reise SO 128.*

2. Cruise participants

„SONNE“ cruise SO 128 was planned, coordinated and led by the Institut für Meereskunde at the University of Kiel, in cooperation with the Institut für Meereskunde of the University of Hamburg (WOCE oceanography).

The shipboard scientific party included 17 scientists, technicians and students. No observers participated in the cruise.

Prof. Dr. Friedrich **Schott**	IfM Kiel
Dorothee **Adam**	IfM Kiel
Kristin **Bahrenfuß**	IfM Kiel
Ralf **Berger**	IfM Kiel
Melanie **Coldewey**	IfM Kiel
Dr. Jürgen **Fischer**	IfM Kiel
Ulf **Garternicht**	IfM Kiel
Meike **Hamann**	IfM Kiel
Torsten **Kanzow**	IfM Kiel
Armin **Köhl**	IfM Kiel
Christian **Lichtenberg**	IfM Kiel
Claus **Meinke**	IfM Kiel
Christian **Mertens**	IfM Kiel
Olaf **Plähn**	IfM Kiel
Rena **Schönefeldt**	IfM Kiel
Dr. Lothar **Stramma**	IfM Kiel
Maren **Walter**	IfM Kiel

Institut für Meereskunde
an der Universität Kiel
Düsternbrooker Weg 20
24105 Kiel
Germany
Tel.: +49 - 431 - 597 - 3820
Fax: +49 - 431 - 597 - 3821

The officers and crew of RV „SONNE“ consisted of 30 members of the Reedereigemeinschaft Forschungsschiffahrt, Bremen.

3. Instrumentation

The hydrographic parameters (temperature, conductivity, pressure and dissolved oxygen) were measured employing a Neil Brown Mark III CTD attached to a 24 bottle rosette water sampler which was also equipped with electronic and mercury deep sea reversing thermometers. Water samples were taken at up to 22 bottles at most stations and analyzed for freon, for salinity with a Guildline Autosal and for dissolved oxygen content using an electronic SIS titration stand. The CTD worked well throughout the cruise. The rosette water sampler, however, showed misfire problems for several days caused by a cable turn inside the ship. The accuracy of the data from pre-cruise laboratory calibration as well as the shipboard calibration with in situ samples is 3 dbar, 0.001 K, 0.002 and 0.07 ml/l for pressure, temperature, salinity and dissolved oxygen content, respectively. The positions of the CTD stations are listed in Table 1 and shown in Figure 1.

In addition, along one section temperature profiles to a depth of 750 m were measured with Sippican expendable bathythermographs (XBT, Figure 1, Table 2).

During cruise SO 128, a 150 kHz Narrow-Band ADCP (NB-ADCP) was mounted in the forward one of the two wells of R/V „SONNE". This instrument was also used during the previous cruise. There were several different navigation sources to support the measurements. The ship's heading information that went into the raw data stream was from the Ashtec 3D GPS providing heading data on a ping to ping basis. Position data were from a RACAL Skyfix system, a long-range differential GPS. As this was the most accurate system available it served as the primary navigation aid. In parallel, we stored combined GPS-GLONASS navigation which is to be recommended for instances when there are data gaps in the differential GPS source.

The scientific crew of the previous cruise reported anomalously large fluctuations (up to 5°) in the differences between the ship's gyro and the Ashtec heading information. This parameter is stored in the ADCP user buffer through the user exit program ue4.exe. The same appeared during some periods of SO 128, and because it was not clear whether this was caused by some failure of the ship's gyro or the Ashtec the latter was recalibrated on January 14, around 8:00 UTC. This resets the mean difference between gyro and Ashtec, which was taken into account during calibration.

The depth range of the shipboard ADCP was near 400 m through most of the cruise. The parameter setting was 8 m bin-length, 16 m pulse width, 4 m delay, and 5' ensemble duration. As the ship's draft is close to 7 m, and bin 1 is usually bad, the center of the first reliable bin is centered at 23 m depth.

An ADCP was lowered with the CTD (LADCP). During the first part of the cruise a Broad-Band ADCP (S/N 1002) was used as LADCP. The instrument had been refurbished prior to the cruise, and it had received a new storage medium, a 20Mb PCMIA-card. Setting the bandwidth narrow, reducing the ambiguity velocity to 240 cm/s and sending pulses twice as long as bins helped to increase the measurement range at depth. This led to considerable reduction in the scatter at depth, allowing to extend the measurements down to the bottom. However, at depth there were sometimes unreliable shears, leading to fictitious intense currents. This was more clearly supported by Pegasus profiles which we carried out in the Somali Basin south of Socotra. The mean differences between Pegasus and LADCP were as small as observed with the Narrow-Band ADCP during earlier cruises, showing the robustness of the barotropic current. But the baroclinic structure showed larger differences than expected. Commonly the LADCP profiles were tilted against Pegasus and showed a first mode structure. Therefore we decided to try the old NB-ADCP during the last two Pegasus stations, and indeed this behaved better.

A special set of data was obtained in the Somali-Socotra Passage, where we made several stations across the passage, with some stations being repeated. By comparing the repeat stations it appeared that the baroclinic structure was roughly the same, but the profiles were shifted. A tidal fit (just based on the few stations) showed amplitudes of ±10 cm/s. When subtracted, currents at the western repeat station (profiles 51,55) were more similar, while the center station was still significantly different. We expect to leam more about this from the tidal components determined by the moored records from the passage.

For determination of the barotropic correction, precise absolute navigation is needed. The long-range differential GPS (RACAL Skyfix-system) of "SONNE" is accurate to a few meters. The resulting error for the relatively long duration of the casts is much less than 1 cm/s and can therefore be neglected.

Six vertical profiles with a free-falling current measurement instrument (PEGASUS) navigated relative to transponders deployed at the ocean bottom were gained at five stations. The transponder pairs were deployed during a METEOR cruise in early 1995 in the western Arabian Sea and were still usable.

Information on surface parameters (meteorological data and surface temperatures and salinities) were collected throughout the cruise from the sensors installed on RV „SONNE“.

4. Listings of station positions

Table 1 *List of CTD/LADCP and Pegasus stations*

Profile	Station	Date	Time	Latitude	Longitude	Water Depth	Profile Depth	Comment
1	57	09.01.98	17:37	7°57.98'N	69°29.96'E	4628	4630	no LADCP
2	58	10.01.98	00:24	8°0.03'N	68°55.03'E	4650	4632	no LADCP
3	59	10.01.98	07:18	8°0.03'N	68°19.97'E	4626	4626	
4	60	10.01.98	14:01	8°0.08'N	67°44.99'E	4626	4626	
5	61	10.01.98	21:21	7°59.91'N	67°10.14'E	4638	4626	
6	62	11.01.98	04:15	7°59.99'N	66°35.03'E	4584	4585	
7	63	11.01.98	11:11	8°0.02'N	66°0.18'E	4588	4589	
8	64	11.01.98	17:56	7°59.99'N	65°25.00'E	4591	1543	
9	65	11.01.98	22:48	7°59.94'N	64°49.99'E	4600	4603	
10	66	12.01.98	05:16	7°59.99'N	64°15.01'E	4594	1539	
11	67	12.01.98	10:01	7°59.95'N	63°39.88'E	4610	4612	
12	68	12.01.98	16:17	7°59.97'N	63°5.00'E	4667	4696	
13	69	12.01.98	22:52	8°0.10'N	62°29.99'E	4849	4854	
14	70	13.01.98	05:30	8°0.26'N	61°54.55'E	4015	4004	
15	71	13.01.98	11:39	8°0.07'N	61°20.03'E	4077	4097	
16	72	13.01.98	17:52	8°0.05'N	60°45.03'E	3446	3353	
17	73	13.01.98	23:48	7°59.99'N	60°9.98'E	3841	3841	
18	74	14.01.98	06:00	8°0.02'N	59°34.98'E	2725	1541	
19	75	14.01.98	10:45	8°0.01'N	59°0.13'E	3530	3477	
20	76	14.01.98	16:33	7°59.97'N	58°24.94'E	3549	1538	
21	77	14.01.98	21:15	7°59.97'N	57°50.11'E	4014	4048	
22	78	15.01.98	03:22	7°59.99'N	57°15.01'E	3651	1543	
23	79	15.01.98	08:07	7°59.97'N	56°40.09'E	3842	3822	
24	80	15.01.98	13:54	7°59.99'N	56°8.08'E	3958	1539	
25	81	15.01.98	18:26	7°59.94'N	55°37.00'E	4078	4124	
26	82	15.01.98	23:11	8°0.02'N	55°20.41'E	5076	4975	
27	83	16.01.98	03:50	8°0.02'N	55°10.06'E	5080	5090	
28	84	16.01.98	09:26	7°59.97'N	54°50.13'E	5074	5085	
29	85	16.01.98	15:28	8°0.05'N	54°25.04'E	5060	5069	
30	86	16.01.98	21:48	7°59.81'N	53°59.73'E	5054	5062	

Profile	Station	Date	Time	Latitude	Longitude	Water Depth	Profile Depth	Comment
31	87	17.01.98	04:00	8°24.03'N	54°3.02'E	5036	5047	
32	88	17.01.98	10:07	8°46.83'N	54°5.95'E	4915	4923	
33	89	17.01.98	16:22	9°10.05'N	54°9.80'E	4749	4750	Pegasus 1
34	90	17.01.98	22:26	9°24.56'N	54°2.60'E	4723	4686	
35	91	18.01.98	03:35	9°39.17'N	53°55.26'E	4611	4579	
36	92	18.01.98	08:48	9°53.79'N	53°48.00'E	4467	4468	Pegasus 2
37	93	18.01.98	14:43	10°7.25'N	53°39.65'E	4351	4315	
38	94	18.01.98	19:37	10°20.74'N	53°31.35'E	4153	4149	Pegasus 3
39	95	19.01.98	00:39	10°34.29'N	53°26.88'E	4058	4029	
40	96	19.01.98	05:00	10°47.72'N	53°22.29'E	3912	3900	Pegasus 4
41	96	19.01.98	09:16	10°47.66'N	53°22.30'E	3931	3901	Pegasus 5
42	97	19.01.98	14:07	10°58.89'N	53°15.08'E	3796	3788	
43	98	19.01.98	18:21	11°10.13'N	53°7.89'E	2850	2842	Pegasus 6
44	99	19.01.98	21:37	11°15.79'N	53°3.51'E	1231	1220	
45	100	19.01.98	23:30	11°22.93'N	52°59.24'E	667	653	
46	101	20.01.98	01:14	11°30.01'N	52°55.04'E	451	440	
47	102	20.01.98	05:14	11°54.02'N	52°27.02'E	248	238	
48	103	20.01.98	06:58	12°0.80'N	52°19.35'E	454	439	
49	104	20.01.98	09:07	12°6.38'N	52°5.42'E	894	889	
50	105	20.01.98	11:07	11°57.48'N	51°56.95'E	1122	1106	
51	106	20.01.98	13:22	11°48.45'N	51°48.41'E	800	799	
52	107	20.01.98	15:00	11°53.00'N	51°52.69'E	1112	1101	
53	108	20.01.98	17:22	12°2.00'N	52°1.23'E	1111	1092	
54	109	20.01.98	19:03	11°57.52'N	51°56.93'E	1116	1108	
55	110	20.01.98	21:10	11°48.46'N	51°48.38'E	795	827	
56	111	20.01.98	22:26	11°51.47'N	51°51.22'E	1036	1029	
57	112	20.01.98	23:56	11°54.48'N	51°54.03'E	1125	1118	
58	113	21.01.98	18:07	12°24.91'N	54°40.95'E	361	366	
59	114	21.01.98	19:15	12°23.01'N	54°45.24'E	999	1004	
60	115	21.01.98	21:18	12°18.96'N	54°52.01'E	2055	2050	

Profile	Station	Date	Time	Latitude	Longitude	Water Depth	Profile Depth	Comment
61	116	21.01.98	23:48	12°14.91'N	55°0.01'E	2534	2519	
62	117	22.01.98	03:53	12°18.90'N	55°20.03'E	3371	3401	
63	118	22.01.98	09:45	12°22.17'N	55°42.95'E	4061	4056	
64	119	22.01.98	16:59	11°37.49'N	55°30.56'E	3863	3856	
65	120	22.01.98	22:00	11°52.89'N	55°41.81'E	4162	1538	
66	121	23.01.98	01:33	12°9.09'N	55°54.01'E	4101	1539	
67	122	23.01.98	05:08	12°26.14'N	56°6.00'E	4115	1540	
68	123	23.01.98	09:03	12°29.84'N	56°29.83'E	4036	4041	
69	124	23.01.98	14:20	12°55.03'N	56°30.00'E	4160	1540	
70	125	23.01.98	18:11	13°20.08'N	56°29.98'E	3854	3854	
71	126	23.01.98	23:18	13°45.02'N	56°30.16'E	2978	1535	
72	127	24.01.98	03:00	14°9.90'N	56°30.01'E	2564	1538	
73	128	24.01.98	07:00	14°34.97'N	56°29.95'E	2487	1538	
74	129	24.01.98	10:52	14°59.91'N	56°30.09'E	2986	1535	
75	130	24.01.98	16:48	15°25.06'N	56°29.96'E	3103	3098	
76	131	24.01.98	21:37	15°49.80'N	56°30.03'E	3124	1576	
77	132	25.01.98	01:29	16°13.98'N	56°37.96'E	3773	3746	
78	133	25.01.98	06:48	16°38.05'N	56°46.94'E	3788	1538	
79	134	25.01.98	09:58	16°55.87'N	56°53.89'E	3812	3806	
80	135	25.01.98	14:26	17°11.99'N	57°1.10'E	3661	3648	
81	136	25.01.98	18:37	17°25.98'N	57°6.03'E	1602	1608	
82	137	25.01.98	21:00	17°34.91'N	57°9.18'E	693	665	
83	138	26.01.98	15:58	19°40.06'N	59°44.98'E	3350	1542	
84	139	26.01.98	19:41	20°4.03'N	59°35.99'E	3234	3207	
85	140	27.01.98	00:15	20°27.97'N	59°28.01'E	2535	2517	no LADCP
86	141	27.01.98	03:38	20°41.34'N	59°23.28'E	1242	1234	no LADCP

LADCP stations:

Profile 3-40 BB-ADCP

Profile 41-84 NB-ADCP

Table 2 *List of XBT stations*

#	Date	UTC	Longitude	Latitude
00	19.01.1998	8:30	053°22.0'E	10°48.0'N
01	22.01.1998	15:25	055°35.0'E	11°54.0'N
02	22.01.1998	15:29	055°34.0'E	11°52.0'N
03	25.01.1998	22:57	057°21.3'E	17°37.0'N
04	25.01.1998	23:58	057°33.6'E	17°39.4'N
05	26.01.1998	1:03	057°45.9'E	17°41.5'N
06	26.01.1998	1:58	057°56.6'E	17°43.4'N
07	26.01.1998	2:57	058°07.5'E	17°45.4'N
08	26.01.1998	3:58	058°18.8'E	17°47.4'N
09	26.01.1998	4:58	058°26.9'E	17°54.8'N
10	26.01.1998	5:59	058°34.2'E	18°04.5'N
11	26.01.1998	5:59	058°34.2'E	18°04.5'N
12	26.01.1998	6:59	058°41.1'E	18°13.9'N
13	26.01.1998	7:59	058°48.0'E	18°23.2'N
14	26.01.1998	8:57	058°54.6'E	18°32.3'N
15	26.01.1998	10:02	059°02.5'E	18°42.6'N
16	26.01.1998	10:57	059°08.9'E	18°51.3'N
17	26.01.1998	12:09	059°16.7'E	19°02.1'N
18	26.01.1998	13:02	059°23.9'E	19°11.5'N
19	26.01.1998	14:08	059°31.6'E	19°22.0'N
20	26.01.1998	15:03	059°38.4'E	19°31.1'N

5. Deliverables

Short cruise report:
The short cruise report was written on board RV „SONNE“ and sent to the Projektträger BEO in Rostock-Warnemünde and the German Ministry of Education, Science, Research and Technology (BMBF) in Bonn on February 2, 1998.

Technical evaluation of the cruise:
The technical evaluation of the cruise SO128 together with SO129 was discussed on 14 April, 1998 at the GEOMAR, Kiel, together with BEO and the Reedereigemeinschaft Forschungsschiffahrt.

Bathymetric data:
The centerbeam bathymetric data from the Hydrosweep system will be edited and sent to the Bathymetric Data Center in Rostock in the near future.

hydrographic data:
The CTD and XBT data will be sent to the appropriate WOCE DAC and to the coastal states for stations within the 200 miles economic zone after final processing.

acoustic velocity measurements:
The ADCP and LADCP data will be sent to the coastal states for measurements within the 200 miles economic zone after final processing.

6. Preliminary results

a) The 8°N section

A main objective of cruise SONNE 128 in January 1998 was to measure a section across the Arabian Sea at 8°N during the winter monsoon and compare the measurements with those taken along 8°N during the summer monsoon by RV SONNE 89 cruise in August 1993. As no research permission was granted for cruise 128 from India and the Maldives, the 8°N section could only be measured west of 69°30'E.

The salinity and oxygen distributions along 8°N in January 1998 are shown in Figures 2 and 3. In addition the T/S-characteristics of CTD-stations performed along 8°N are depicted in Figure 4. One question is whether and where Red Sea Water reaches the 8°N section. As one can see in the T/S-diagram and the salinity distribution, a slight increase of salinity from 35 psu to 35.25 psu occured near the 27.25 isopycnal, which is the core density range of Red Sea Water (RSW). The high-salinity RSW leaves the Red Sea through the Strait of Bab el Mandeb and spreads into the Gulf of Aden and the Arabian Sea and can be seen east of 64°E in the salinity measurements along 8°N (Figure 2).

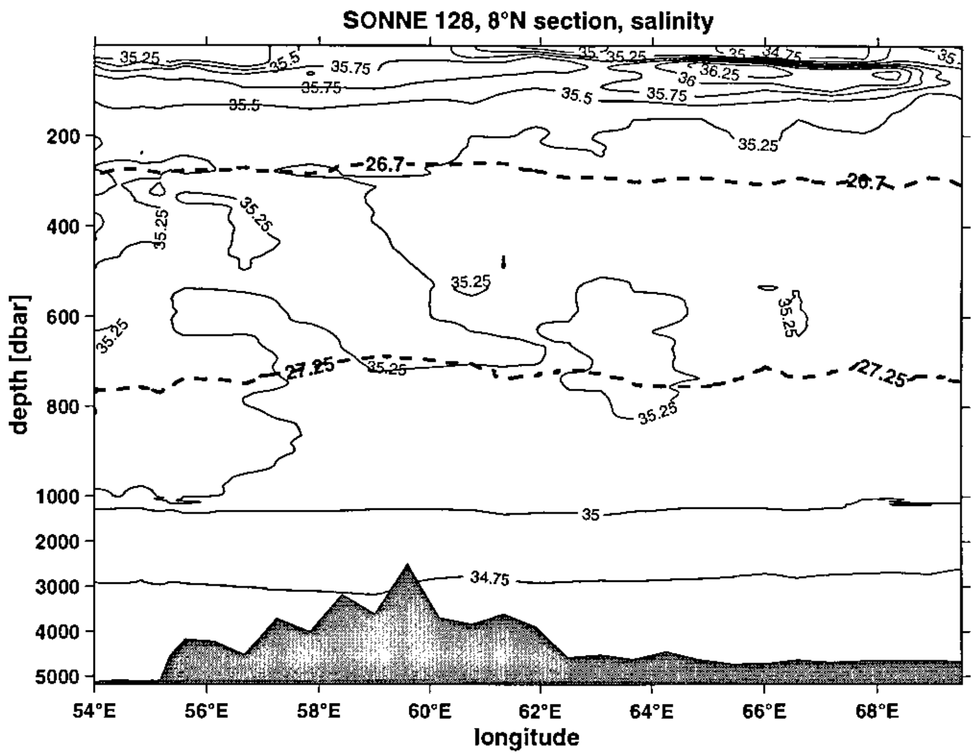

Figure 2: *Salinity distribution along 8°N in January 1998. Note the change of scale at 1000 dbar depth. Included are the two isopycnals 26.7 and 27.25, representing the core density of Persian Gulf Water and Red Sea Water, respectively.*

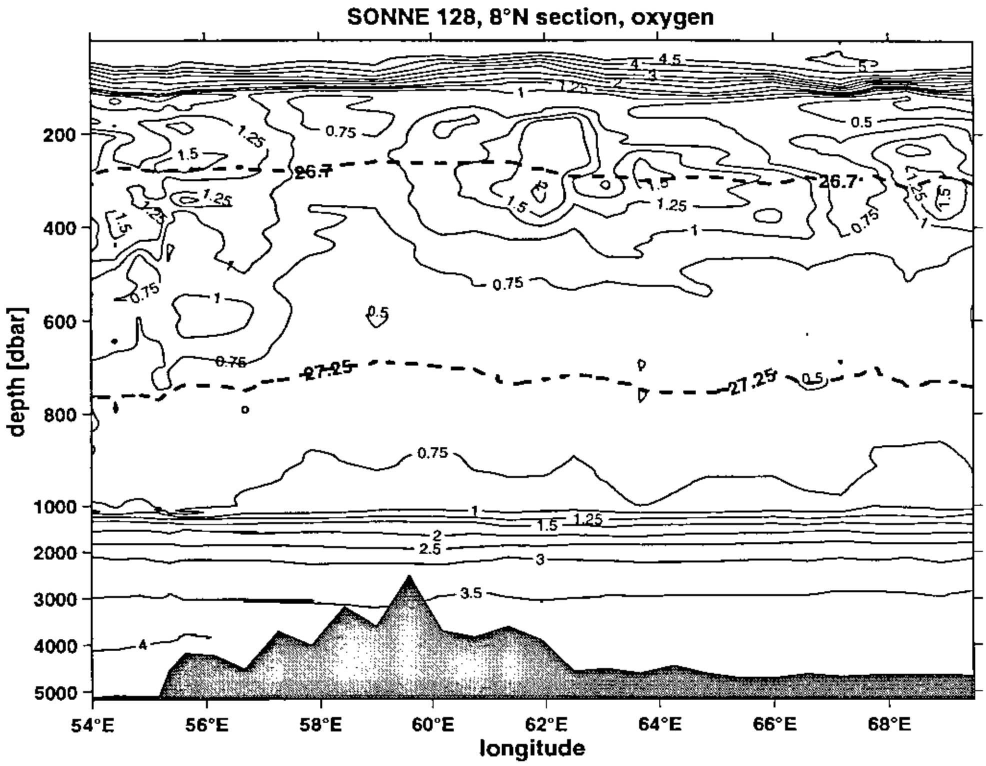

Figure 3: *Same as Figure 2, but for oxygen in ml/l.*

A subsurface salinity maximum was present between 30 and 150 dbar (Figure 2), with a sea surface salinity (SSS) minimum directly above. West of 63°E the salinity decreased from more than 36.25 psu to less than 34.75 psu. Salinities between 36.2 and 36.4 psu are typical for Arabian Sea Water (ASW) in this part of the Arabian Sea. Further north the values were even higher. In the T/S-diagram the salinity maximum of ASW is clearly evident. The SSS minimum was due to the inflow of low-salinity Bay of Bengal Water (BBW) during the N-E-monsoon. During the S-W-monsoon the BBW was forced back to the east by the Ekman transport and is replaced by more saline waters from the central Arabian Sea.

The oxygen distribution (Figure 3) shows the well known oxygen minimum in the depth range between 500 and 1000 dbar. A shallow oxygen minimum in the thermocline at about 150 m depth, as expected for the Arabian Sea, was also seen. Between these two minima an intermediate oxygen maximum was situated near the 26.7 isopycnal centered at 62°W with oxygen values of 1 to 2 ml/l. One might expect Persian Gulf Water (PGW) on this sigma-θ-surface, but as there was neither a signal in the salinity distribution nor any hint of PGW in the T/S-diagram, the increase of oxygen originated from Indian Central Water (ICW). ICW is formed in the subpolar region near 45°S, where it sinks down along the 26.7 isopycnal and carries water with more than 5.5 ml/l oxygen to the north.

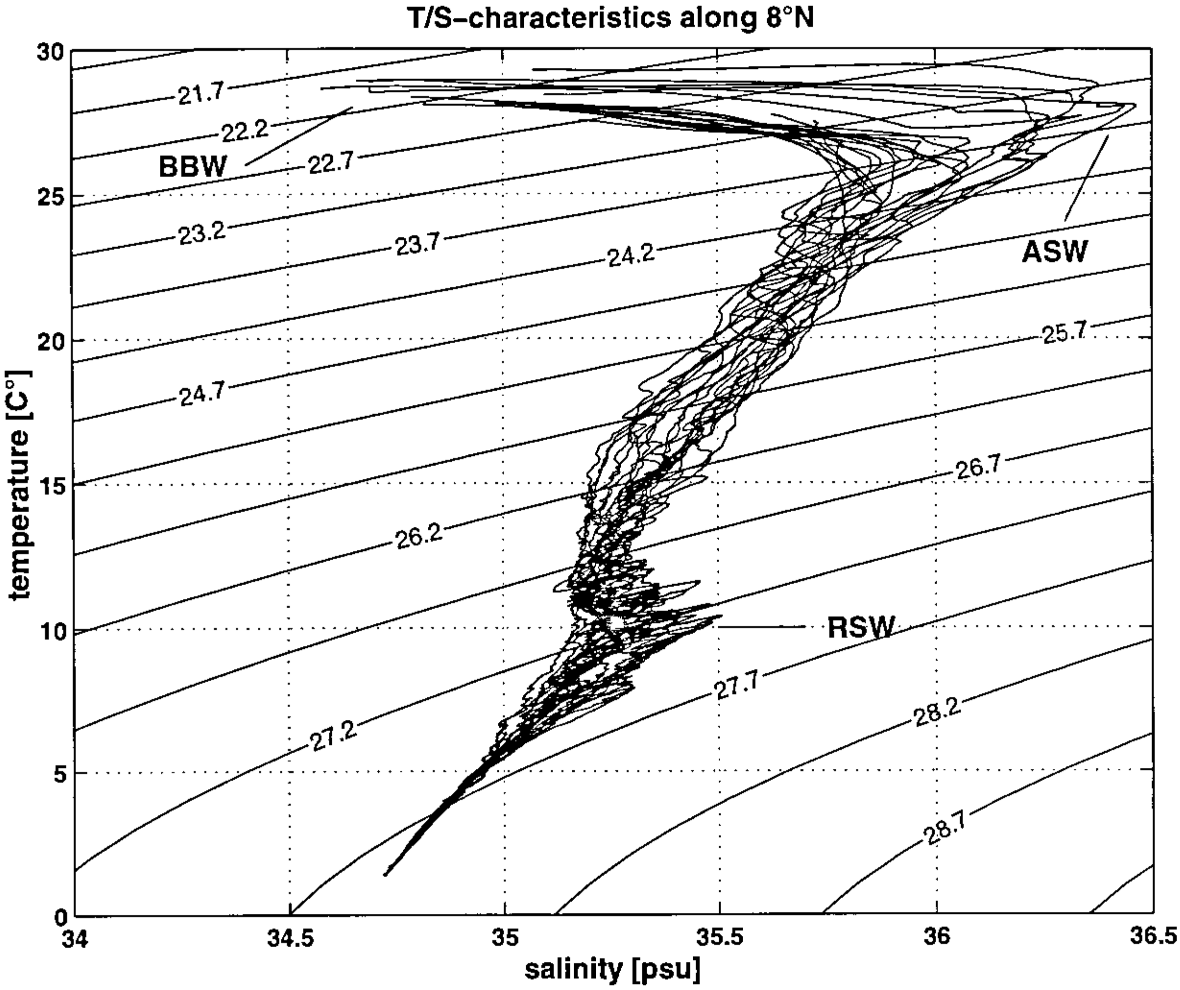

Figure 4: *T/S-characteristics from CTD-stations along 8°N. The influence of water masses of Red Sea Water (RSW), Arabian Sea Water (ASW) and Bay of Bengal Water (BBW) is indicated.*

A first comparison between the winter and the summer monsoon velocity distribution is shown in Figure 5 from direct velocity observations with shipboard ADCP. There is a remarkable difference in the velocity field. At most locations the flow direction between summer and winter monsoon was reversed and the velocities were weaker in January 1998 than in August 1993. A transport of 40 Sv to the south in the upper 400 m could be seen in August 1993 between 54°E and 56°E caused by the southward component of the Great Whirl. The northward component was located to the west within the 200 miles zone of Somalia, not covered during the cruise. While the Great Whirl recirculated as an almost closed cell, the water brought into the Arabian Sea in August moved north just east of the Great Whirl and showed water

Arabian Sea in August moved north just east of the Great Whirl and showed water mass characteristics of Indian Equatorial Water (IEW). The transport imbalances indicate that the velocity distribution in the near surface layer was influenced by the Ekman transports. During January 1998 the N-E-monsoon caused northeastward Ekman transports and there was a net northward transport, while the S-W-monsoon caused a southeastward Ekman transport and in August the net transport across the section segment was to the south.

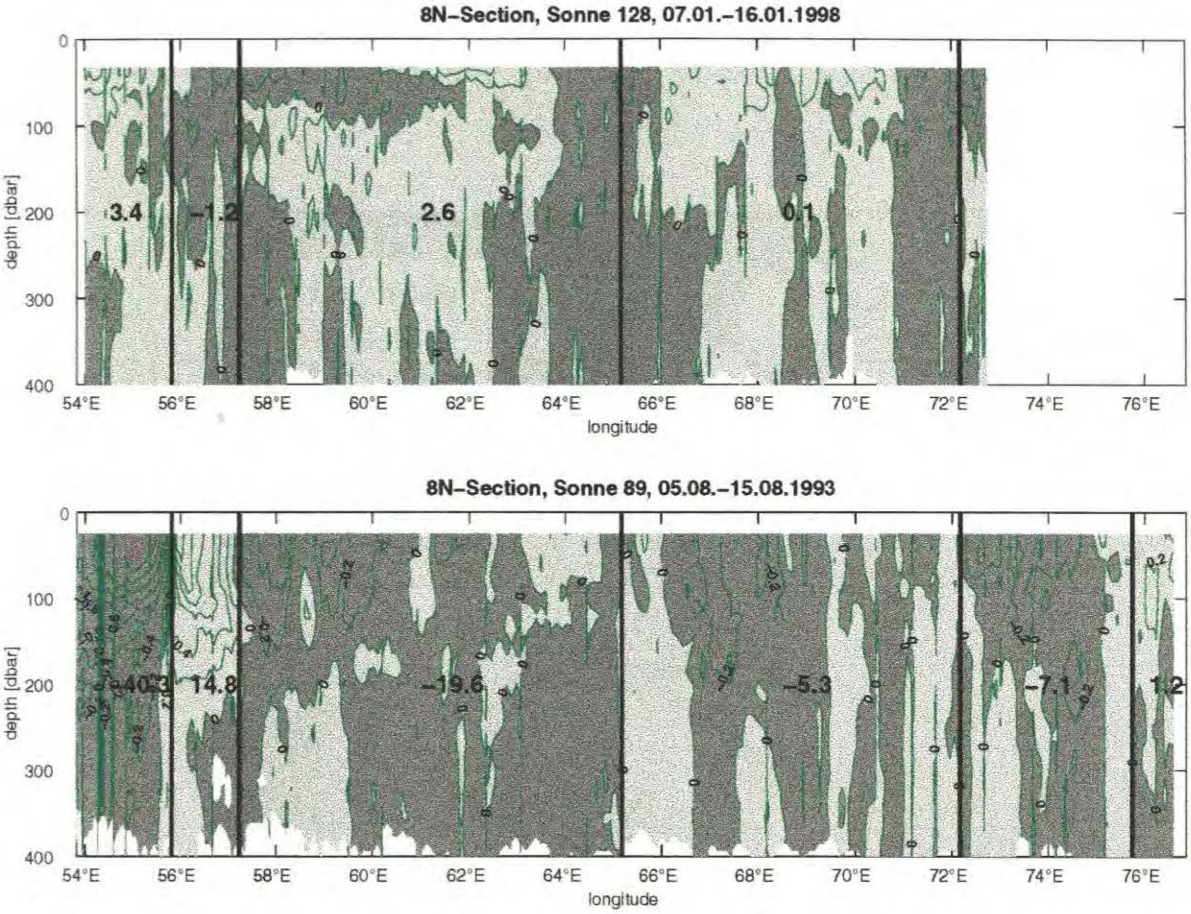

Figure 5: *Comparison of the shipboard ADCP velocities in m/s for the upper 400 m along 8°N for January 1998 and August 1993 (dark shading to the south). The velocities east of 69°30'E in January 1998 were taken during cruise SO 127 on a section tilted leg towards the southeast. Transports in Sv between the thick vertical lines are given as thick numbers.*

b) Large scale flow field observed by shipboard- and lowered ADCP

In the western Arabian Sea north of 8°N currents in January 1998 were generally surface-intensified with strong shear in the depth range between 100 m to 200 m. Along 8°N and in the passage between Somalia and the island of Abd Al Kuri this led to a total reversal of the flow averaged over 150 m to 250 m compared to the near surface flow (Figures 6 and 7). Cyclonic rotation of the currents was found near the Somali coast south of the island of Socotra. There a strong (up to 40 cm/s) inflow into the boundary current existed between 9°N and 11°N, and immediately south of it the offshore return flow crossed the western end of the 8°N section in northeastward direction. To the north this flow split up into a component parallel to the coast of Socotra (eastward) and a component flowing into the Gulf of Aden. However, the westward inflow was confined to the shallow top layer (above 100 m) with outflow underneath.

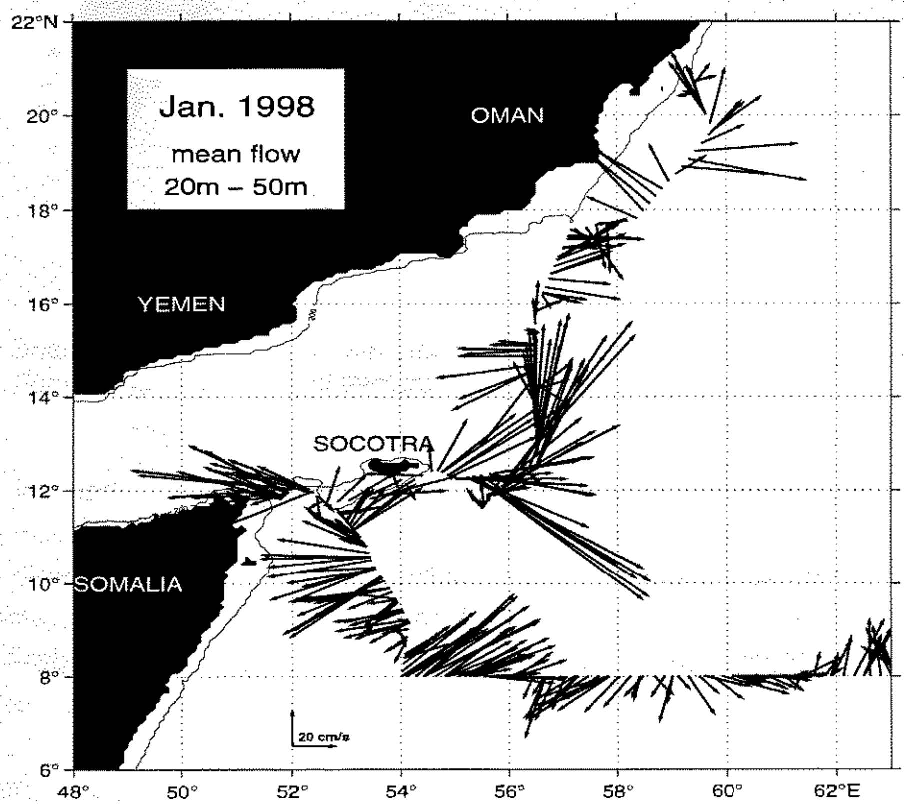

Figure 6: *Near surface flow from shipboard ADCP measurements averaged over the depth range 20 - 50 m. For scaling of the current vectors see lower left.*

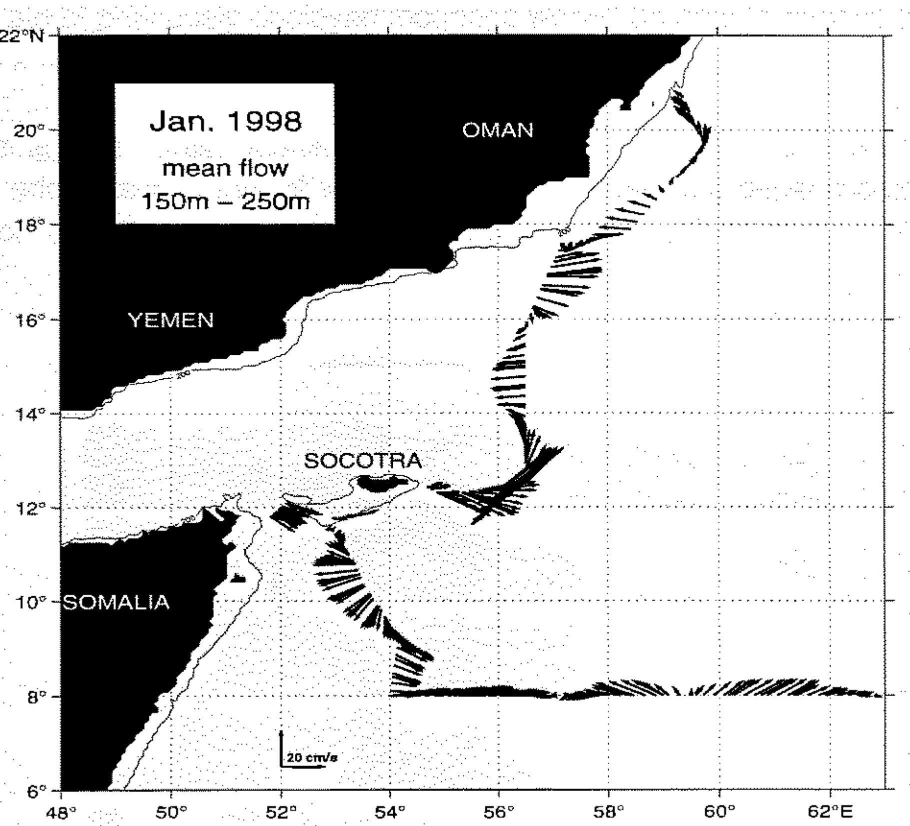

Figure 7: *Shipboard ADCP measurements averaged over the depth range 150 - 250 m. For scaling of the current vectors see lower left.*

The most intense currents during the cruise were observed southeast of Socotra showing a meander or eddy structure with the flow direction turning from eastward to northward directions along the northward section at 57°E. Further north the flow then turned westward (inflow into the Gulf of Aden). Outflow was then again observed near the Arabian Peninsula at 16°N to 18°N. Further up the coast the currents showed alternating onshore and offshore directions.

For the deeper layers, beyond the range of the shipboard ADCP, the LADCP data are of great importance. One example is the exchange of Red Sea Water (RSW) through the passage between Somalia and Abd al Kuri (Figure 8). Below the very intense surface flow confined to the upper 100 m there was a deep inflow into the Somali Basin at the western side of the passage showing a current core of more than 35 cm/s near 700 m depth which was associated with Red Sea Water by its high salinity. At the eastern side of the passage the deep flow was in opposite direction (inflow into the Gulf of Aden). However, transport budgets are difficult to calculate, as there is a strong tidal component superimposed on the flow. We hope that with the calculate, as there is a strong tidal component superimposed on the flow. We hope that with the aid of previously deployed moorings we will be able to remove the tides for obtaining a reliable estimate of the throughflow through the passage.

In summarizing, the winter monsoon flow in the western Arabian Sea showed complicated eddy-like currents of which a proper analysis will depend crucially on the evaluation of water mass distributions, satellite data (altimetry and SST) and model data.

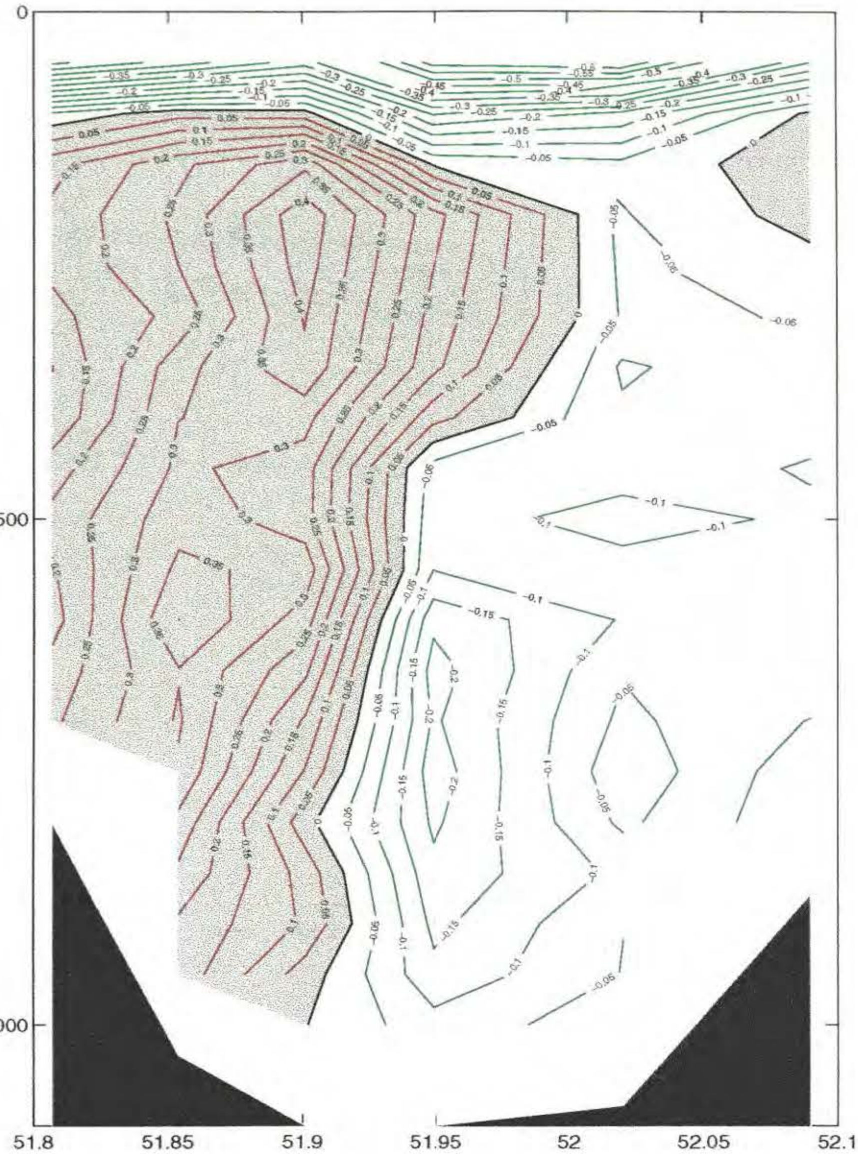

Figure 8: *Cross-section flow through the passage between Somalia (to the west) and the island of Abd al Kuri to the east. Data are from the lowered ADCP (LADCP). Shaded area is for flow out of the Gulf of Aden into the Somali Basin.*

c) Hydrographic observations in the northern Arabian Sea

During the summer and winter monsoon the currents in the northern Arabian Sea change direction and strength and consequently have an impact on the water mass distribution and spreading paths. As an example for the winter monsoon water mass distribution the salinity (Figure 9) and oxygen (Figure 10) sections from east of Sokotra towards the Oman coast at about 56°E are described here. Included in the figures are the isopycnals 26.7 (typical core density of Persian Gulf Water) and 27.25 (typical core density of Red Sea Water), to find out whether these water masses are present in this section.

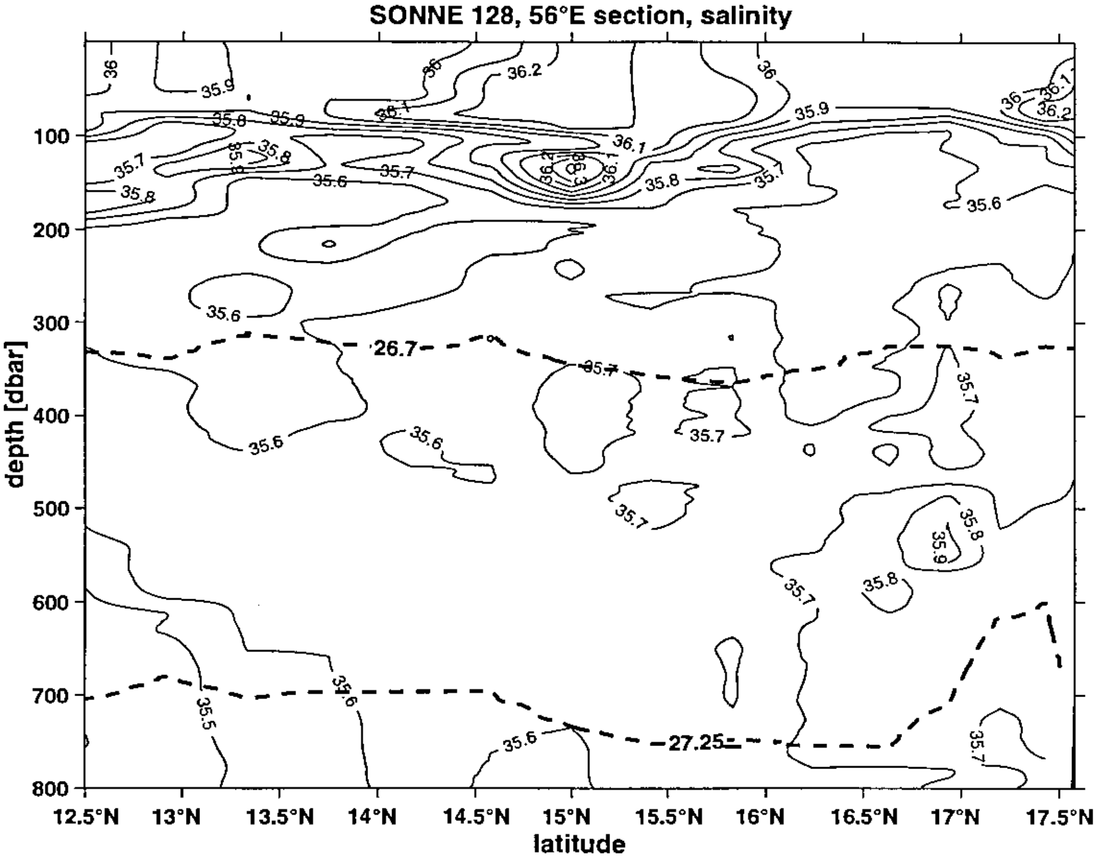

Figure 9: *Salinity distribution between profiles 68 and 82 (see Figure 1) at about 56°E at the end of January 1998. The isopycnals 26.7 near 350 dbar (Persian Gulf Water) and 27.25 near 700 dbar (Red Sea Water) are included as broken lines.*

The largest salinities in the top 150 dbar (Figure 9) were located between the profiles 73 and 77 at about 15°N. According to the velocity distribution (Figures 6 and 7) the salinity maximum was located at the northern end of an westward-flowing current band, which transported saline Arabian Sea Water towards the west. Near the isopycnal 26.7 no enhanced salinities were observed (Figure 9), indicating that, similar to the 8°N section no Persian Gulf Water was detectable in the salinity distribution in the 56°E section in January 1998. However, CFC data (see d) showed, that at the southern end of the section the water at 26.7 originated from the Persian Gulf. Neither was Red Sea Water observed at the isopycnal 27.25 in the salinity and oxygen distributions. However north of 16°N near the Omani coast enhanced salinities at 500 to 800 m indicated some flow of Red Sea Water towards the east. This eastward spreading of Red Sea Water is in agreement with observed eastward currents at that depth in the lowered ADCP records. However, in January 1998 the largest signal of Red Sea Water was observed in the Socotra Passage.

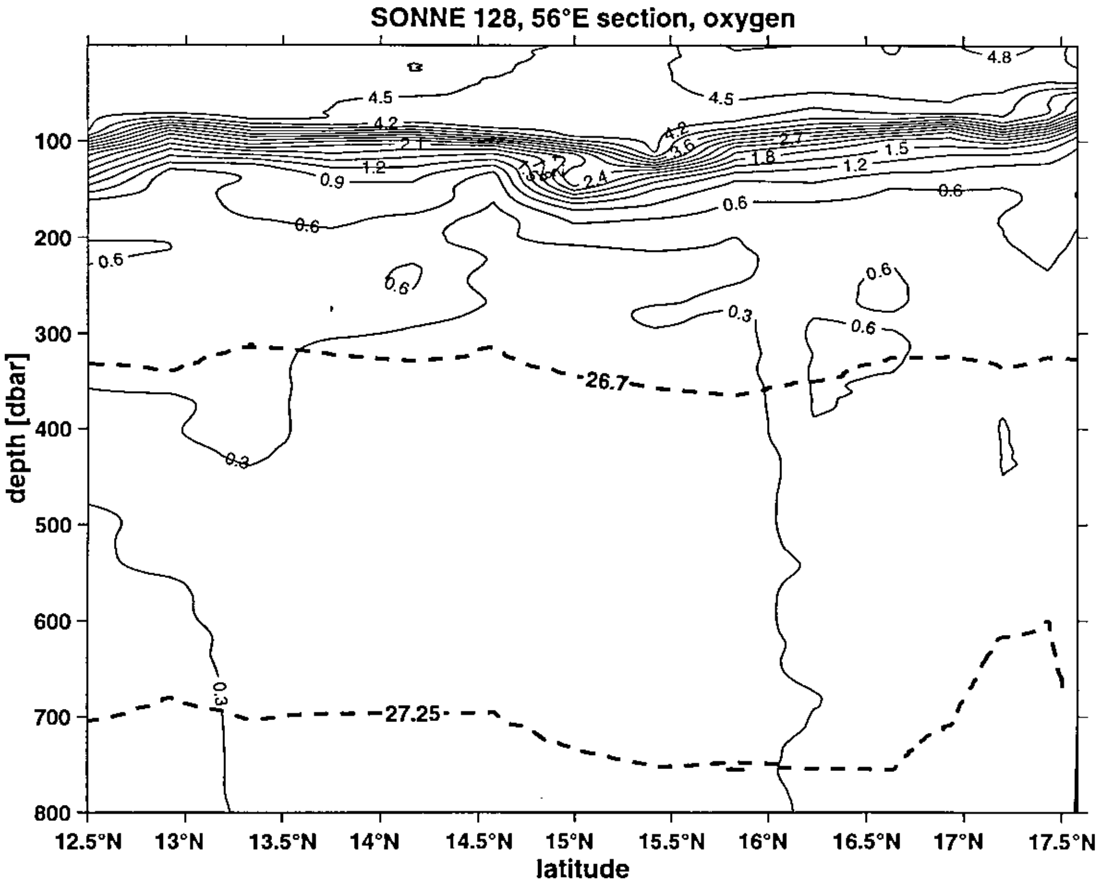

Figure 10: *Same as Figure 5, but for dissolved oxygen [in ml/l].*

The central Arabian Sea is known for a low-oxygen layer with almost no detectable dissolved oxygen at intermediate depth, approximately 1 km thick. Previous studies speculated that this minimum is caused by very slow movement in this layer. However, the oxygen budget for the layer in more recent investigations supports the idea that the near-zero concentration is maintained by moderate consumption applied to waters with initially low oxygen concentrations that pass through the layer at moderate speed. Figure 10 shows the low oxygen layer below 200 dbar and high dissolved oxygen values were observed only in the surface-mixed layer in the upper 100 m. For the layer 200 to 800 m, the lowered ADCP showed westward velocities of typically 5 to 10 cm/s between 13.5°N and 16°N, eastward velocities of 5 cm/s south of 13.5°N, 10 to 20 cm/s between 16°N and 17.3°N and weak westward flow near the shelf-break. The oxygen distribution reflects well the velocity distribution, with the lowest oxygen (below 2ml/l) coming from the central Arabian Sea between 13.5 and 16°N while the eastward flowing regions to the north and the south showed slightly higher oxygen values (of about 0.4 ml/l). These observations are in agreement with the idea that the current in the oxygen minimum layer has moderate speed and that the contribution to this layer like the Red Sea Water north of 16°N enters to this water mass with low oxygen concentrations of about 0.4 ml/l.

d) CFC Analysis

Additional information of water mass distribution and its time history can be gained from the freon (CFC) analysis. As the CFC measurements are not familiar to many people, first some information on the measurement technique is presented here.

During the SONNE 128 cruise CFC components CFC-11 and CFC-12 were analysed. About 1100 samples on 70 CTD stations were measured with a gas chromatographic technique using an Electron Capture Detector (ECD). The efficiency of the ECD decreased to 65% for CFC-11 and 45% for CFC-12 at the end of the cruise. To correct this temporal drift of the ECD, calibrations before and after each station were made. To check the accuracy of the measurements more than 10% of the samples were analysed twice or more. The accuracy was +/-1.4% for both components and the mean blank (determined by degasing 1-2 mL of CFC-free deep water) was 0.008 pmol/kg for CFC-12 and 0.012 pmol/kg for CFC-11.

Additionally, air samples inside (laboratory) and outside (clean air) the vessel were taken regularly and analysed. The concentrations of the "clean air" measured on the vessel were about 550 ppt for CFC-12 and 270 ppt for CFC-11, which were higher than "real" clean air, caused by emission from the ship. The values inside the vessel were a little (ca. 15 ppt) higher. From previous measurements (WOCE Meteor cruises in 1995) in the Arabian Sea it is known that the freon concentration decreased exponentially from the surface to about 1000 m depth. Now, the detection limit decreased to larger depth, but below 1500 m depth no CFC signal could be detected and therefore most of the CFC samples were collected in the upper 1500 m meter. The surface was saturated to about 110+/-5% in the whole observed area. This value was larger than observed in 1995 and will be analysed and compared with model results in the future.

In 1995, a subsurface CFC-12 maximum was found in the Gulf of Oman, bounded vertically between 200-350 m depth, in the Persian Gulf (PGW) outflow regime. At that time, the new characteristic of the PGW was concentrated within a small area at the coast of Oman with saturation of more than 250%. During the SONNE 128 cruise this signal was found near the Omani coast at 59°E and in the central Arabian Sea east of Socotra (Figure 11). Thus "young" PGW spreads within about 2 years into the western Arabian Sea. A mean transport of less than 0.5 Sv was calculated for PGW assuming a mean dilution rate of 30% from the source signal in the Gulf of Oman to the western Arabian Sea.

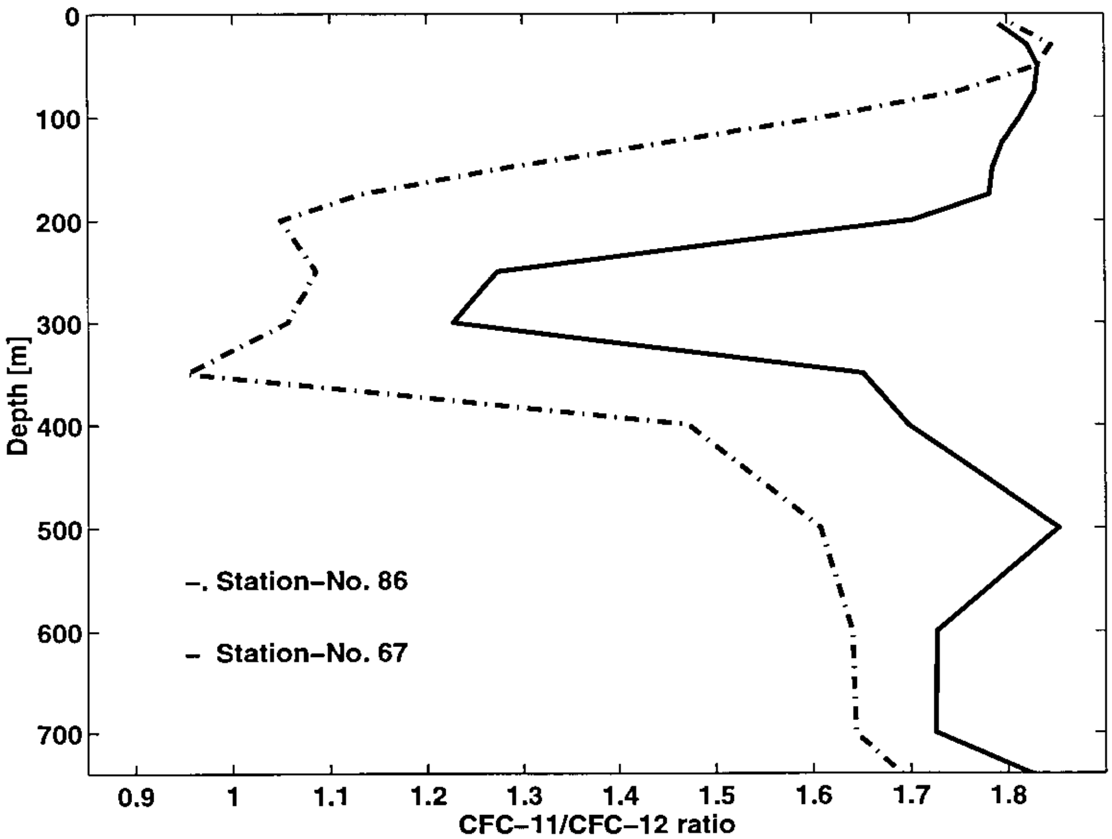

Figure 11: *CFC-11/CFC-12 ratio measured at the coast of Oman (Stat.86) and east of Socotra (Stat.67). The minimum between 200-300 m depth is caused by large CFC-12 values spreading from the Persian Gulf.*

Acknowledgements

We like to thank Captain Dierck Kalthoff and his crew for their support of the scientific work at sea. Financial support for this study was given by the Bundesforschungsminister für Bildung, Wissenschaft, Forschung und Technologie under grant 03G0128A (ARABWOCE).